

TPS Design for Neptune Aerocapture Vehicle using Closed-Loop Trajectory Simulation

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Aerocapture has been studied extensively over past twenty years and has repeatedly been shown to produce significant payload gains for missions to atmosphere-bearing planets. However, because of the large approach navigation errors and uncertainties in the Neptunian atmosphere, there will be significant dispersions in an aerocapture trajectory. This in turn will translate into an expanded design envelope for the thermal protection system (TPS), and an increase of its mass-fraction for the aerocapture vehicle.

Aerocapture at Neptune stresses the TPS design due to very high heat loads, stagnation point heat load can be up to 2000 kJ/cm², in comparison, Galileo was 850 kJ/cm². Hence, there is a need for design of a guidance scheme that would demonstrate reduced dispersions in maximum heating rate and integrated heat load in the presence of extreme off-nominal atmospheres, approach guidance errors and off-nominal vehicle characteristics. This will enable the reduction the TPS mass-fraction for the aerocapture vehicle.

To carry out the proposed investigation, a new closed-loop trajectory simulation with a predictor-corrector guidance algorithm was developed and applied to a Neptune aerocapture vehicle.¹ The outer loop in this simulation is used to represent the motion of an aerocapture vehicle in the perturbed planetary atmosphere, while the inner loop of the simulation is used as a guidance algorithm to target the vehicle to the desired orbital apoapse and inclination at atmospheric exit, while constraining the integrated heat load. The aerocapture trajectories were analyzed for inertial entry velocity of 29 km/sec. This entry velocity results from fast interplanetary transfer, which would employ low thrust nuclear-electric propulsion in order to reduce time in transit to Neptune down to 8-10 years. The mission profile consisted of a single atmospheric pass, which is controlled through bank angle as well as angle of attack modulation, to insert the vehicle into an elliptic orbit with an exit apoapse altitude of 400,000 km. This allows close passage of the vehicle to Neptune's moon Triton. The vehicle has a biconic configuration with L/D of 0.9 at 35.5 deg trim angle, and its angle of attack modulation range is limited between 31 to 40 deg, i.e. ± 4.5 deg from trim angle.

For chosen entry vehicle configuration, the use of the proposed guidance scheme allowed successful aerocapture for a wide range of off-nominal conditions, which are likely to be encountered at Neptune. A nominal aerocapture trajectory was simulated in the presence of various combinations of dispersions in atmospheric density, entry angle and vehicle aerodynamics. The guidance scheme developed for this investigation, demonstrated that in a realistic aerocapture environment, where various dispersions are present, the integrated heat load could be significantly reduced as compared to that of the overshoot. It was found that the use of guidance by means of bank angle and angle of attack modulation decreased the integrated heat load for the worst off-nominal case by 51% compared to that of the nominal overshoot, while maximum heating rate was reduced by 23% compared to the nominal undershoot. Established design practice uses the heat load associated with overshoot to define TPS material thickness distribution over aeroshell. The higher value of integrated heat load, associated with overshoot, requires thicker TPS material to maintain desired limit on bondline temperature. Therefore, the TPS based on results obtained for the vehicle guided by bank and angle of attack modulation will be significantly lighter. Another important result is that the use of angle of attack modulation, besides enhancing guidance of aerocapture vehicle, also allows to constrain its integrated heat load.² In summary, it can be concluded that use of guidance scheme employing bank and angle of attack control enables a more mass-efficient TPS for an aerocapture vehicle.

Furthermore, the relative benefits of this approach increase for the aerocapture missions whose destinations are gas-giants, where very high entry velocities can be expected.

References: 1. Jits, R. Y., Walberg, G. D., "Blended Control, Predictor-Corrector Guidance: An Enabling Technology for Mars Aerocapture," Paper IAF-01-A.7.05, Toulouse, France, October 2001.
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